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DEFENCE RESEARCH ESTABLISHMENT OTTAWA
REPORT NO.1032

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ABSTRACT

The degree of protection from neutron irradiation afforded to electronics by armoured vehicles is most correctly defined by the outside-to-inside ratio of the 1 MeV equivalent neutron fluence for Silicon. It has been proposed that this factor may be approximated by an experimentally measurable parameter - the neutron (tissue kerma) reduction factor. This report examines the validity of this assumption for a variety of realistic nuclear battlefield scenarios, calculated using the computer code VPF2. In addition the response of two neutron dosimeters in the calculated fields is examined.

RESUME

Le degré de protection des composantes électroniques contre les irradiations de neutrons reçues est correctement défini par le rapport de pénétration extérieur-vers-l'intérieur de 1 MeV équivalent de fluence silicium. Il a été proposé que facteur pouvait être représenté par un paramètre mesurable, le facteur de réduction de neutron (tissue kerma). Ce rapport étudie la validité de cette hypothèse pour une variété de scénarios possibles en utilisant le programme VPF2. De plus, la réponse de deux dosimètres de neutrons est étudiée.

EXECUTIVE SUMMARY

In order to predict the degree of protection afforded to electronics by armoured vehicles exposed to neutron irradiation, the ratio of outside to inside tissue kermas has often been used as an approximation. This report examines the validity of this approximation by using the computer code VPF2 to generate neutron fields to be expected in a number of battlefield scenarios. The performance of two neutron dosimeters in these fields is also examined.

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1.0 INTRODUCTION

The protection factor afforded by armoured vehicles to the deleterious effects of radiation from nuclear weapons is a subject of much concern to the NATO community - so much so that it has spawned an entire Allied Engineering Publication (AEP-14) (1). While the document is extremely thorough in addressing the issue of protection of personnel, only minor mention is made of the protection afforded to electronics. In particular, when considering the damage created by neutron irradiation of semiconductors, the concept of 1 MeV equivalent neutron fluence is generally used (2). AEP-14 states only that the neutron protection afforded to electronics may be approximated by the neutron reduction factor -which is essentially a ratio of tissue kermas. This work strives to examine the validity of this approximation for a variety of battlefield scenarios using the latest DREO-developed computational capabilities.

2.0 METHODOLOGY

2.1 DEFINITION OF FACTORS

The characterization of radiation protection factors afforded by armoured vehicles necessitates the definition of a number of protection factors. These are all based on the neutron and gamma-ray energy spectra both inside and outside the vehicle being convolved with an appropriate response function, and the subsequent evaluation of their ratio, i.e.

$$(XPF)_R = \frac{\int \phi_{outside}(E)\ R(E)\ dE}{\int \phi_{inside}(E)\ R(E)\ dE} \qquad (1)$$

where

$(XPF)_R$ = general protection factor for parameter having energy response $R(E)$

$\phi_{inside}(E)$ = particle fluence inside vehicle

$\phi_{outside}(E)$ = particle fluence outside vehicle

Based on the general definition of (1), any protection factor may be calculated. From AEP-14 the most commonly used factors - namely the neutron and gamma-ray reduction and protection factors (in which R(E) is the tissue kerma response function) are defined as:

(i) Gamma-Ray Protection Factor

$$GPF = \frac{\text{Gamma Ray Kerma Outside Vehicle}}{\text{Kerma Due to Gamma Rays Penetrating Vehicle}} \qquad (2)$$

(ii) Neutron Protection Factor

$$NPF = \frac{\text{Neutron Kerma Outside Vehicle}}{\text{Neutron Kerma Inside Vehicle + Armour-generated Secondary Gamma Ray Kerma}} \qquad (3)$$

(iii) Gamma-Ray Reduction Factor

$$GRF = \frac{\text{Gamma-Ray Kerma Outside Vehicle}}{\text{Gamma-Ray Kerma Inside Vehicle}} \quad (4)$$

(iv) Neutron Reduction Factor

$$NRF = \frac{\text{Neutron Kerma Outside Vehicle}}{\text{Neutron Kerma inside Vehicle}} \quad (5)$$

For neutron irradiation of semiconductor materials, the major damage-causing mechanism is displacement of silicon atoms due to elastic (and inelastic) collisions. Thus the Silicon Displacement Kerma energy response is the important parameter as R(E) in eqn(1). However the normal procedure for characterizing semiconductor damage is to reduce the neutron fluence to the equivalent fluence of 1 MeV neutrons (2), i.e.

$$\phi_{eq}(1\ \text{MeV}) = \frac{\int \phi(E)\ K_D(E)\ dE}{K_D(1\ \text{MeV})} \quad (6)$$

where

ϕ_{eq} (1 MeV) = 1 MeV equivalent neutron damage in Si

K_D (E) = neutron displacement kerma factor for Si

K_D (1 MeV) = neutron displacement kerma factor for 1 MeV neutrons

$= (3.26 +/- 0.14) \times 10^{-11}$ Rad-cm^2 (3)

Calculation of the 1 MeV equivalent neutron fluance allows definition of the 1 MeV equivalent neutron reduction factor as:

$$CRF = \frac{\int \phi_{outside}(E)\ K_D(E)\ dE}{\int \phi_{inside}(E)\ K_D(E)\ dE} \quad (7)$$

The comparison of the CRF (which is the direct measure of the effectiveness of vehicle shielding for neutron damage to electronics) to NRF (which is an experimentally measurable approximation) is the main thrust of this work

Of course, knowledge of the both inside and outside energy spectra allows direct evaluation of dosimeter performance and many other relevant parameters some of which will be glanced upon here.

2.2 COMPUTER CODES

In order to evaluate the inside and outside energy spectra at realistic distances from simulated nuclear weapons the computer code VPF2 (4) (in a slightly modified form) was used. The code is micro-computer based and menu driven. It uses an interface with another code - ATR5 (5)- to generate two-dimensional angular fluence data at the vehicle range.

The two-dimensional data is then collapsed into effective one-dimensional fluences which are then used as a source term for ANISN slab radiation transport calculations into the vehicle. As a result the protection and reduction factors calculated by VPF2 are effectively averaged over all azimuthal vehicle orientations within the free-field.

For this work, a special modification of VPF2 allowing particle energy spectra output was employed.

Fig (1) should clarify the VPF2 methodology.

2.3 WEAPON SPECIFICATIONS

To make the comparisons meaningful, the entire gamut of energy spectra likely to be encountered on the battlefield should be covered. To accomplish this, three separate source spectra were employed. They were:

(a) The standard fission weapon (SFW) source spectrum from ATR5
(b) The thermonuclear weapon (TNW) source spectrum from ATR5
(c) A source consisting entirely of 14 MeV neutrons (14 MeV)
Appendix (A) lists source spectra (a) and (b).

The yields chosen here were 5 kT and 100 kT for each weapon, with the source normalizations being 2×10^{23} n/kT and 5×10^{22} g/kT for the SFW case and 1.2×10^{24} n/kT for the TNW and 14 MeV cases. No gamma-ray source term was used with either the TNW or 14 MeV cases since recent DREO calculations have shown (6) that the contribution to total dose from prompt gamma rays is generally dwarfed by that from neutron-capture gamma rays.

The height-of-burst (HOB) for the weapons were chosen as that which would maximize blast effects, i.e.

$$HOB = 60\ (YIELD)^{1/3} \qquad (8)$$

Thus the HOBs were 102.6 m and 278.5 m for the 5 kT and 100 kT bursts respectively.

The air-over-ground calculations used the default air and ground elemental composition and moisture content from ATR5.

The dose constraint option within ATR5 was used to give the ranges from the weapons at which free-field neutron tissue kermas of 450 Rads (LD_{50}) and 2500 Rads (ITI) would occur. The vehicle was then placed at these ranges and the VPF2 calculations commenced.

2.4 VEHICLE TYPES

Since the purpose of this report was chiefly to compare ORF to NRF, which are ratios, it was decided that extremely simplistic vehicles would suffice. However these model vehicles would need enough detail to show broad differences in vehicle design, such as thin-walled (APC) vs thick-walled (tank) vehicles with

and without the addition of a liner. Accordingly the vehicle types described in table (1) were employed. All are a simple 2m x 2m x 2m (outside dimensions) cube.

TABLE 1

SIMULATED VEHICLE TYPES

CODE	DESCRIPTION
V1	2" thick Al walls
V2	6" thick steel walls
V3	2" thick Al walls with 2" thick polyethylene liner on inside
V4	6" thick steel walls with 2" thick polyethylene liner on inside

2.5 DOSIMETER RESPONSE

The calculation of the response of a dosimeter in an arbitrary field depends upon knowledge of the radiation energy spectrum in that field, plus the energy spectrum of the radiation field in which the dosimeter was calibrated.

Then defining R_{cal} and K_{cal} as the detector response and tissue kerma, respectively, in the calibration field, i.e

$$R_{cal} = \int \phi_{cal}(E)\ R_D(E)\ dE \tag{9}$$

$$K_{cal} = \int \phi_{cal}(E)\ K_T(E)\ dE \tag{10}$$

where

ϕ_{cal} = radiation fluence in calibration field

$R_D(E)$ = energy-dependent detector response (arbitrary units)

$K_T(E)$ = energy-dependent tissue kerma response

Then one may define a calibration factor, C, as

$$C = K_{cal}/R_{cal} \tag{11}$$

Now when the dosimeter is exposed to an arbitrary fluence field, $\phi_{field}(E)$, the measured response (again in arbitrary units) will be

$$M = \int \phi_{field}(E)\ R_D(E)\ dE \tag{12}$$

Then the 'dose'(K_D) indicated by the dosimeter is simply

$$K_D = C\ M \tag{13}$$

A comparison of K_D with the true radiation field tissue kerma (i.e. replace 'cal' with 'field' in eqn (10)) gives the efficacy of the dosimeter in that particular field.

It was decided here to examine the responses of two neutron dosimeters in the calculated fields. They are the proposed CF neutron dosimeter (which is a Silicon diode(7)) and the super-heated drop or 'bubble' dosimeter (8) which has become DREO's principal experimental neutron dosimeter over the past few years and which, in the future, may see direct military applications. Each dosimeter deserves some further discussion.

For the case of the diode, the detector response function was assumed to be identical to the silicon displacement kerma(9) - which merely assumes that there is little detector escape probability. The calibration factor is then simply the ratio of the energy weighted tissue kerma response to the energy weighted silicon displacement kerma response in the calibration field.

When considering the bubble detector the energy response, as obtained by the manufacturer (10), as shown in fig(2) was used.

The choice of an appropriate calibration field is somewhat arbitrary. Here a ^{252}Cf fission source is assumed - although other common sources such as Pu-Be would not change the results greatly. The ^{252}Cf source has the distinct advantage of a well-defined semi-empirical fit to its energy distribution (the Watt spectrum) as

$$\phi_{Cf}(E) = 0.373 \exp(-0.88E) \sinh(\sqrt{2E}) \quad n\ cm^{-2}\ s^{-1}\ MeV^{-1} \tag{14}$$

Using these the derived calibration factors are

$$C(\text{diode}) = 74.6 +/- 3.2 \quad \text{Rad(tissue)/Rad(Silicon)} \tag{15}$$

$$C(\text{bubble}) = 9.31\times10^{-5} +/- 10\% \quad \text{Rad(tissue)/bubble} \tag{16}$$

3.0 RESULTS

3.1 EXPERIMENTAL RESULTS

Owing to the lack of sophisticated neutron spectroscopic equipment, experimental data on NRF and ORF is very limited. However one recent experiment at Aberdeen Proving Ground (APG) used the most sophisticated neutron spectrometer (ROSPEC) available for free-field and in-vehicle work (11). Here the neutron spectra were measured at the NATO standard reference point- 400 m from the critical facility core both free-field and in the 'NATO standard test bed' (12). The test bed is actually a 2m x 2m x 2m cube having 4" thick steel walls.

The results of this work are presented in table (2), together with calculational results from VPF2 and more exotic codes.

TABLE 2

RESULTS FROM TEST BED EXPERIMENTS AND CALCULATIONS

METHOD	NRF	ORF
ROSPEC	1.48	1.43
VPF2*	1.78	
SAIC calculations(13)	1.60	
ORNL calculations(13)	1.58	
ETCA calculations(13)	1.44	

*VPF2 results modified to reflect internal scattering

The VPF2 and other calculations used an old source term and the air and ground moisture were not matched to those present during the experimental measurements. The ratio of calculation to experiment for the four cases is (1.08 +/- .09), which gives some confidence to the results to be presented.

The ROSPEC-measured spectra for both inside and outside cases are shown in fig (3). They may both be considered as degraded fission spectra with mean energies of 0.50 and 0.77 MeV respectively. The comparison here between ORF and NRF is excellent - within 3%. This agreement may have been expected when one examines fig (4) - a ratio of the tissue- and silicon displacement kerma factors. The overall trend is reasonably flat here. Still there exists enough structure that some spectral variations in the ORF approximation to NRF may occur, making this study important.

3.2 CALCULATIONAL RESULTS

3.2.1 FREE-FIELD RANGES AND SPECTRA

The ranges at which the ATR5 calculations yieded the LD50 and ITI neutron kermas appear in table (3). Some of the free-field spectra appear in fig (5).

TABLE 3

RANGES FOR STATED EFFECT

WEAPON	RANGE (m) LD50	ITI
SFW - 5 kT	970.5	750
SFW - 100 kT	1430.5	1177
TNW - 5 kT	1289.2	1015.8
TNW - 100 kT	1845.6	1545.9
14 MeV- 5 kT	1579.8	1280.7
14 MeV-100 kT	2166.8	1851

3.2.2 DOSIMETER RESPONSE

Tables (4),(5) and (6) give the predicted dosimeter responses for the neutron diode and bubble detectors(as compared to free-field) for the SFW, TNW and 14 MeV cases respectively. Listing of some of the calculated energy spectra appear in Appendix B.

TABLE 4

DOSIMETER RESPONSES(rads) IN SFW ENVIRONMENTS

5 kT weapon

(a) NOMINAL LD50 RANGE

CASE	TISSUE	N-DIODE	RATIO*	BUBBLE	RATIO*
FF	446	427	0.96	641	1.43
V1	324	308	0.95	459	1.42
V2	115	113	0.98	207	1.80
V3	63.8	62.5	0.98	77.6	1.22
V4	12.9	12.4	0.96	19.4	1.56
		MEAN	.97+/-.01		1.49+/-.21

(b) NOMINAL ITI RANGE

CASE	TISSUE	N-DIODE	RATIO*	BUBBLE	RATIO
FF	2480	2370	0.95	3640	1.47
V1	1800	1710	0.95	2600	1.44
V2	648	633	0.98	1170	1.80
V3	339	331	0.98	423	1.25
V4	70.6	67.7	0.96	108	1.52
		MEAN	.96+/-.02		1.50+/-.20

100 kT weapon

(a) NOMINAL LD50 RANGE

CASE	TISSUE	N-DIODE	RATIO*	BUBBLE	RATIO
FF	447	431	0.96	605	1.35
V1	329	316	0.96	441	1.34
V2	113	111	0.98	199	1.76
V3	74.3	72.9	0.98	84.8	1.14
V4	13.9	13.4	0.96	20.1	1.45
		MEAN	.97+/-.01		1.41+/-.22

(b) NOMINAL ITI RANGE

CASE	TISSUE	N-DIODE	RATIO*	BUBBLE	RATIO
FF	2480	2380	0.96	3470	1.40
V1	1820	1740	0.96	2510	1.37
V2	636	621	0.97	1130	1.78
V3	381	374	0.98	450	1.18
V4	74.2	71.3	0.96	110	1.48
		MEAN	.97+/-.01		1.44+/-.22

* RATIOS OF DOSIMETER READINGS TO FF KERMA

TABLE 5

DOSIMETER RESPONSES(RADS) IN TNW ENVIONMENTS

5 kT weapon

(a) NOMINAL LD50 RANGE

CASE	TISSUE	N-DIODE	RATIO	BUBBLE	RATIO
FF	449	433	0.96	511	1.14
V1	337	324	0.96	387	1.15
V2	110	108	0.98	180	1.64
V3	109	105	0.96	105	0.96
V4	18.8	17.9	0.95	23.1	1.23
		MEAN	0.96+/-.01		1.22+/-.25

(b) NOMINAL ITI RANGE

CASE	TISSUE	N-DIODE	RATIO	BUBBLE	RATIO
FF	2610	2500	0.96	2990	1.14
V1	1940	1860	0.96	2250	1.16
V2	643	629	0.98	989	1.54
V3	625	599	0.95	603	0.96
V4	110	105	0.95	134	1.21
		MEAN	0.96+/-.01		1.19+/-.20

100 kT weapon

(a) NOMINAL LD50 RANGE

CASE	TISSUE	N-DIODE	RATIO	BUBBLE	RATIO
FF	449	435	0.97	501	1.11
V1	340	329	0.97	382	1.12
V2	109	107	0.98	178	1.63
V3	112	108	0.96	107	0.96
V4	18.6	17.8	0.96	23	1.23
		MEAN	.97+/-.01		1.21+/-.25

(b) NOMINAL ITI RANGE

CASE	TISSUE	N-DIODE	RATIO	BUBBLE	RATIO
FF	2500	2410	0.96	2800	1.12
V1	1890	1820	0.96	2130	1.12
V2	608	597	0.98	989	1.62
V3	620	598	0.96	594	0.96
V4	104	99.4	0.95	128	1.23
		MEAN	.96+/-.01		1.21+/-.24

TABLE 6

DOSIMETER RESPONSE IN 14 MEV ENVIRONMENT

5 kT weapon

(a) NOMINAL LD50 RANGE

CASE	TISSUE	N-DIODE	RATIO	BUBBLE	RATIO
FF	450	432	0.96	475	1.05
V1	340	327	0.96	366	1.07
V2	109	106	0.97	172	1.57
V3	123	117	0.95	112	0.91
V4	20.8	19.6	0.94	24.1	1.16
		MEAN	.96+/-.01		1.15+/-.25

(b) NOMINAL ITI RANGE

CASE	TISSUE	N-DIODE	RATIO	BUBBLE	RATIO
FF	2610	2500	0.96	2990	1.19
V1	1880	1800	0.95	1990	1.06
V2	602	588	0.97	941	1.56
V3	702	665	0.94	631	0.89
V4	121	113	0.93	136	1.12
		MEAN	.95+/-.02		1.16+/-.25

100 kT weapon

(a) NOMINAL LD50 RANGE

CASE	TISSUE	N-DIODE	RATIO	BUBBLE	RATIO
FF	449	434	0.97	483	1.07
V1	341	330	0.96	372	1.09
V2	108	106	0.98	174	1.61
V3	119	114	0.96	111	0.93
V4	19.6	18.7	0.95	23.5	1.19
		MEAN	.96+/-.01		1.17+/-.25

(b) NOMINAL ITI RANGE

CASE	TISSUE	N-DIODE	RATIO	BUBBLE	RATIO
FF	2490	2400	0.96	2640	1.06
V1	1890	1820	0.96	2040	1.08
V2	600	588	0.98	952	1.59
V3	679	649	0.95	623	0.92
V4	113	107	0.95	132	1.16
		MEAN	.96+/-.01		1.16+/-.25

The two main features evident from the preceding tables are (a) the excellent performance of the neutron-diode and (b) the poor performance of the bubble dosimeter. The first feature may be attributed to statistically negligible spectral changes when considering the different environments or, should such differences exist, their masking by energy-binning effects. In either case, the neutron-diode is an extremely accurate dosimeter for these fields.

The case of the bubble detector deserves more discussion. The reason for the wide variations from tissue kerma may be grasped from an examination of fig(6). Here the dosimeter response is plotted in a more appropriate fashion as a ratio of expected bubbles per tissue kerma. Note the large peaking in the region around a few hundred keV. Now consider fig(7) in which the free-field and V2 cases for the TNW are shown. The free-field spectrum is relatively flat and the predicted bubble response is close (within 12 %) to tissue kerma. However for the shielded case, the spectrum is highly peaked, unfortunately in the same energy region as the bubble detector response peak - leading to a 60 % over-estimate in kerma.

However, actual experimental data with the bubble detector does not back these results. Take the APG experiments mentioned earlier. Bubble detectors were deployed for this work. The measured responses were 3.83 and 2.78 mRad/kWh for the free-field and in-box cases respectively(11). Using the same procedure as above(i.e using the ROSPEC measured spectra as the input energy spectra and folding into the bubble detector energy-fluence response) the predicted bubble detector kermas would be 7.63 and 6.66 mrad/kWh respectively. The measured NRF would then be 1.38 as compared to the calculated 1.15. This, and other reliable experimental work with the bubble detectors, suggests that the energy response function is not accurate, and more work needs to be done in this area.

Clearly, with the excellent agreement between the neutron-diode response and tissue kerma, the CRF/NRF approximation must be extremely good here. Table (7) merely reinforces this point.

TABLE 7

COMPARISON OF ORF TO NRF VALUES

SFW WEAPON - LD50 RANGE

	5 kT		100 kT	
	NRF	ORF	NRF	ORF
V1	1.38	1.39	1.36	1.36
V2	3.87	3.78	3.94	3.88
V3	6.99	6.82	6.02	5.91
V4	34.5	34.3	32.1	32.1

SFW WEAPON - ITI RANGE

	5 kT		100 kT	
	NRF	ORF	NRF	ORF
V1	1.38	1.39	1.36	1.37
V2	3.83	3.75	3.9	3.83
V3	7.34	7.17	6.51	6.37
V4	35.2	35.1	33.4	33.4

TNW WEAPON - LD50 RANGE

	5 kT		100 kT	
	NRF	ORF	NRF	ORF
V1	1.33	1.33	1.32	1.32
V2	4.07	4.00	4.11	4.06
V3	4.13	4.13	4.00	4.02
V4	23.9	24.2	24.1	24.4

TNW WEAPON - ITI RANGE

	5 kT		100 kT	
	NRF	ORF	NRF	ORF
V1	1.34	1.34	1.32	1.32
V2	4.05	3.97	4.11	4.04
V3	4.17	4.17	4.03	4.04
V4	23.6	23.9	23.9	24.3

14 MEV WEAPON - LD50 RANGE

	5 kT		100 kT	
	NRF	ORF	NRF	ORF
V1	1.32	1.32	1.32	1.32
V2	4.14	4.05	4.14	4.08
V3	3.67	3.69	3.78	3.80
V4	21.7	22.0	22.9	23.3

TABLE 7 (Continued)

COMPARISON OF ORF TO NRF VALUES

14 MEV WEAPON - ITI RANGE	5 kT		100 kT	
	NRF	ORF	NRF	ORF
V1	1.33	1.32	1.32	1.32
V2	4.15	4.05	4.16	4.09
V3	3.56	3.58	3.67	3.70
V4	20.7	21.0	22.1	22.5

4. CONCLUSIONS AND RECOMMENDATIONS

The use of the neutron reduction factor as a means of estimating the silicon displacement damage to semiconductors has been proven valid for a variety of cases. As an additional output of this work the efficacy of the neutron diode dosimeter in these fields has also been demonstrated. The absolute value and shape of the bubble dosimeter energy response is brought into question by the theoretical and experimental results presented here.

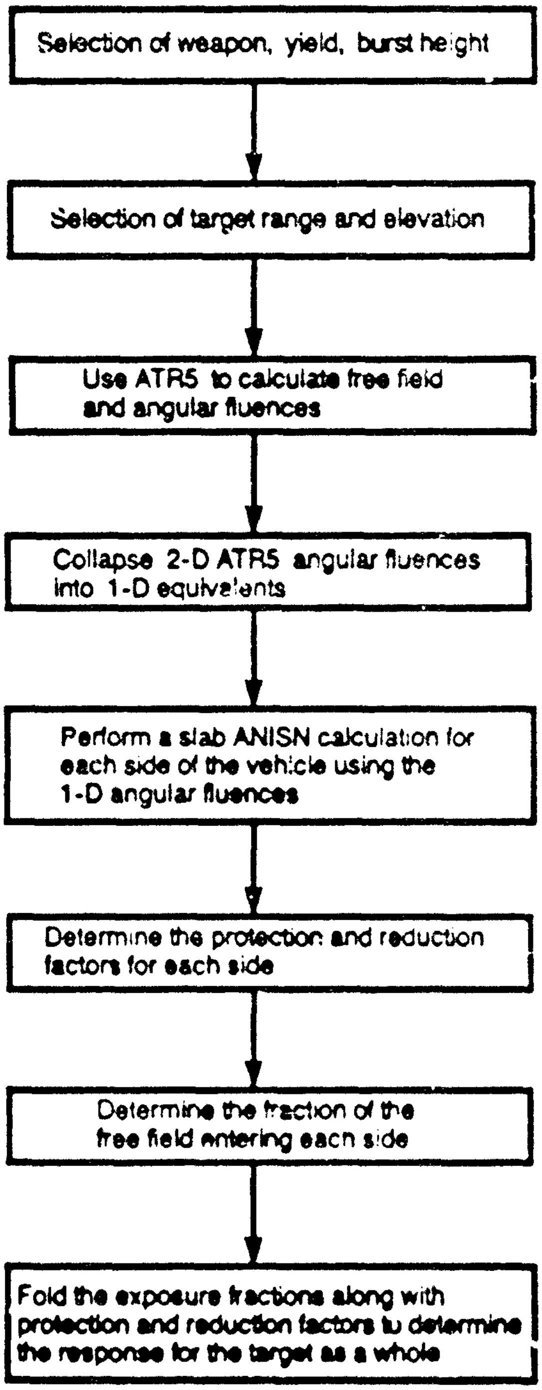

FIGURE 1 VPF2 Methodology

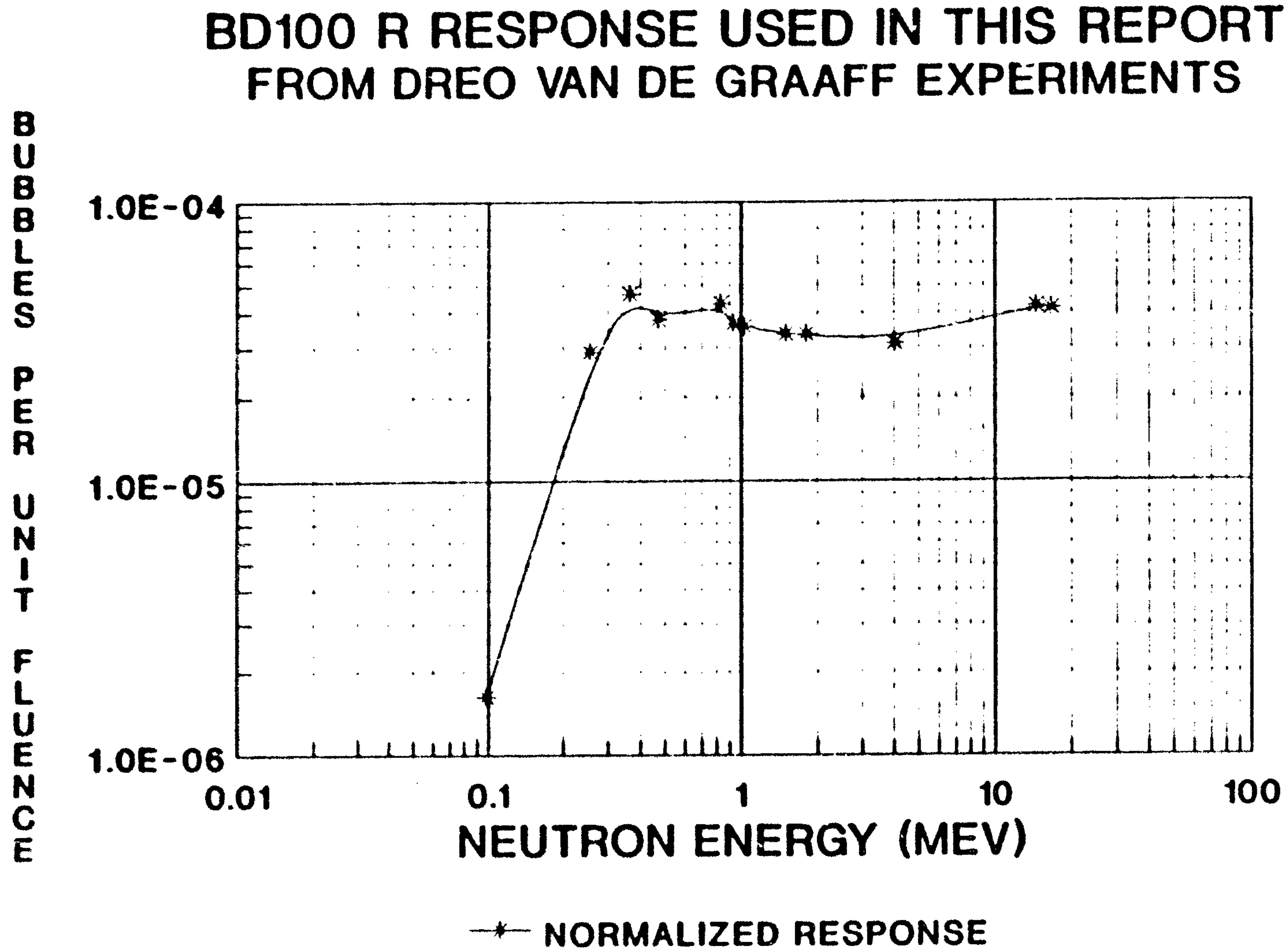

FIGURE 2 BD100R fluence/energy response used in this report.

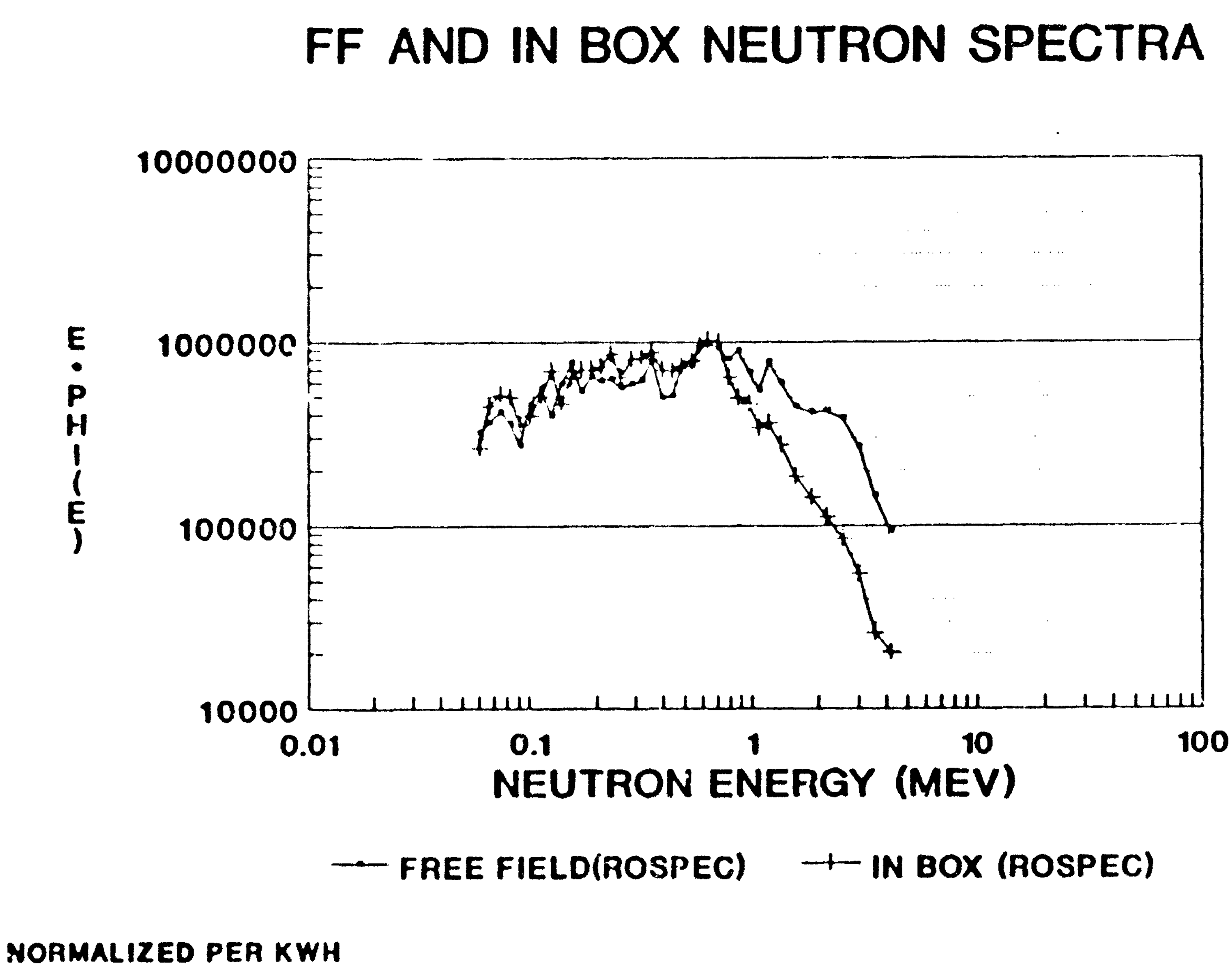

FIGURE 3 Measured (ROSPEC) neutron energy spectra both free-field (at the NATO standard reference point) and in the test bed configuration.

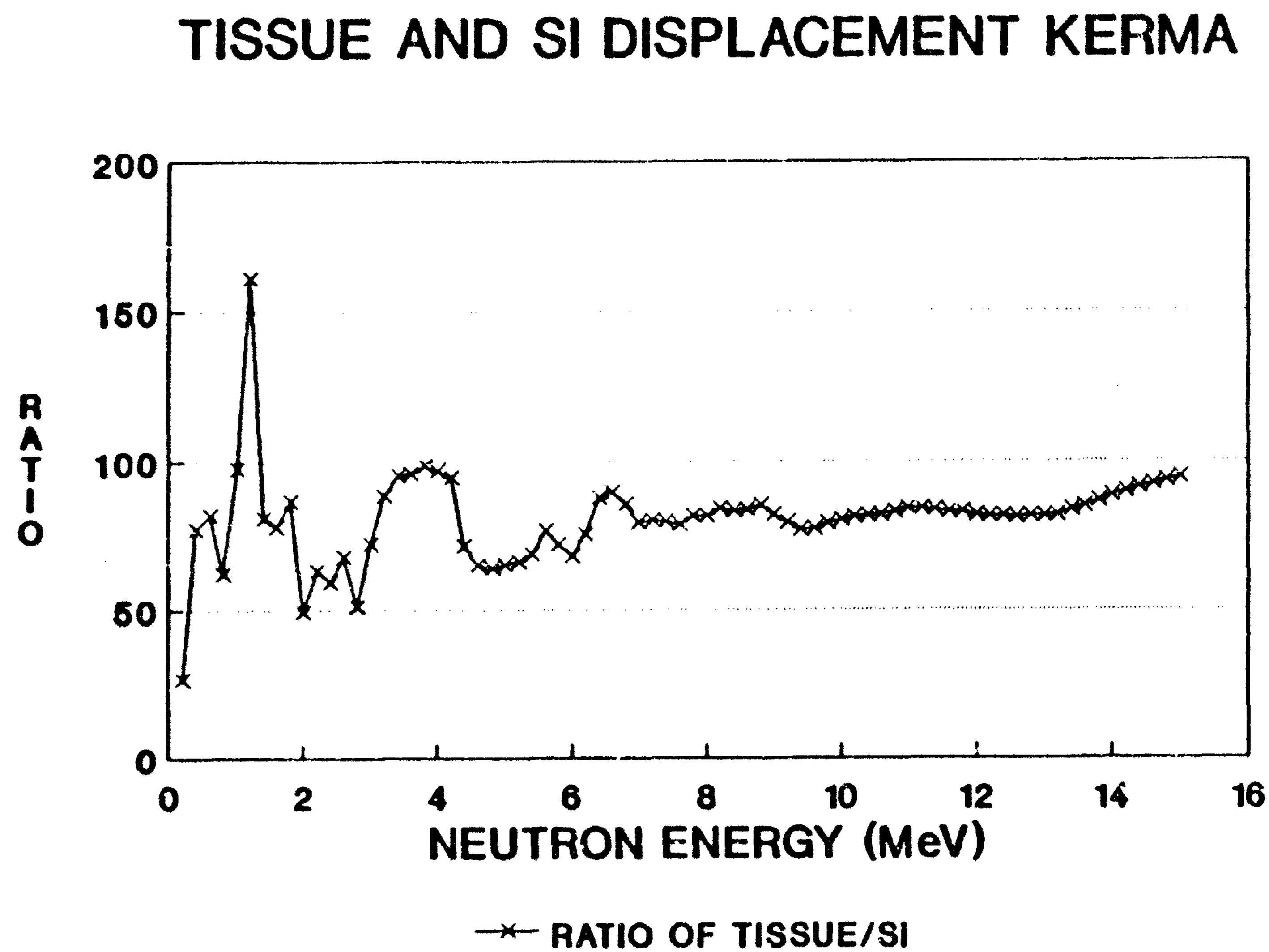

FIGURE 4 Ratio of neutron tissue kerma to neutron displacement kerma in Si. Note the structure riding on a fairly flat base.

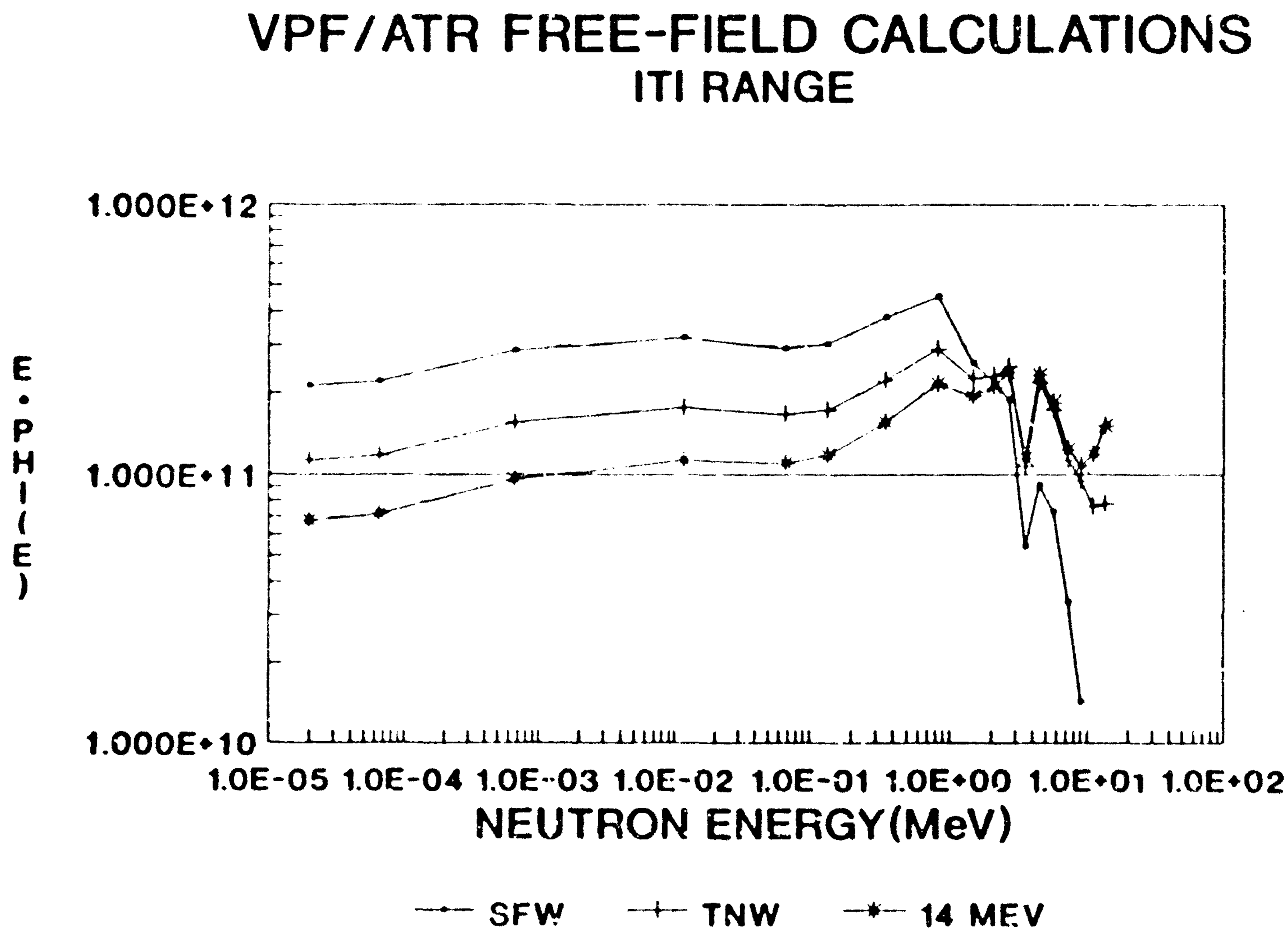

FIGURE 5   Free field neutron energy spectra (for the ITI case) as calculated by ATR5 for the three weapon scenarios.

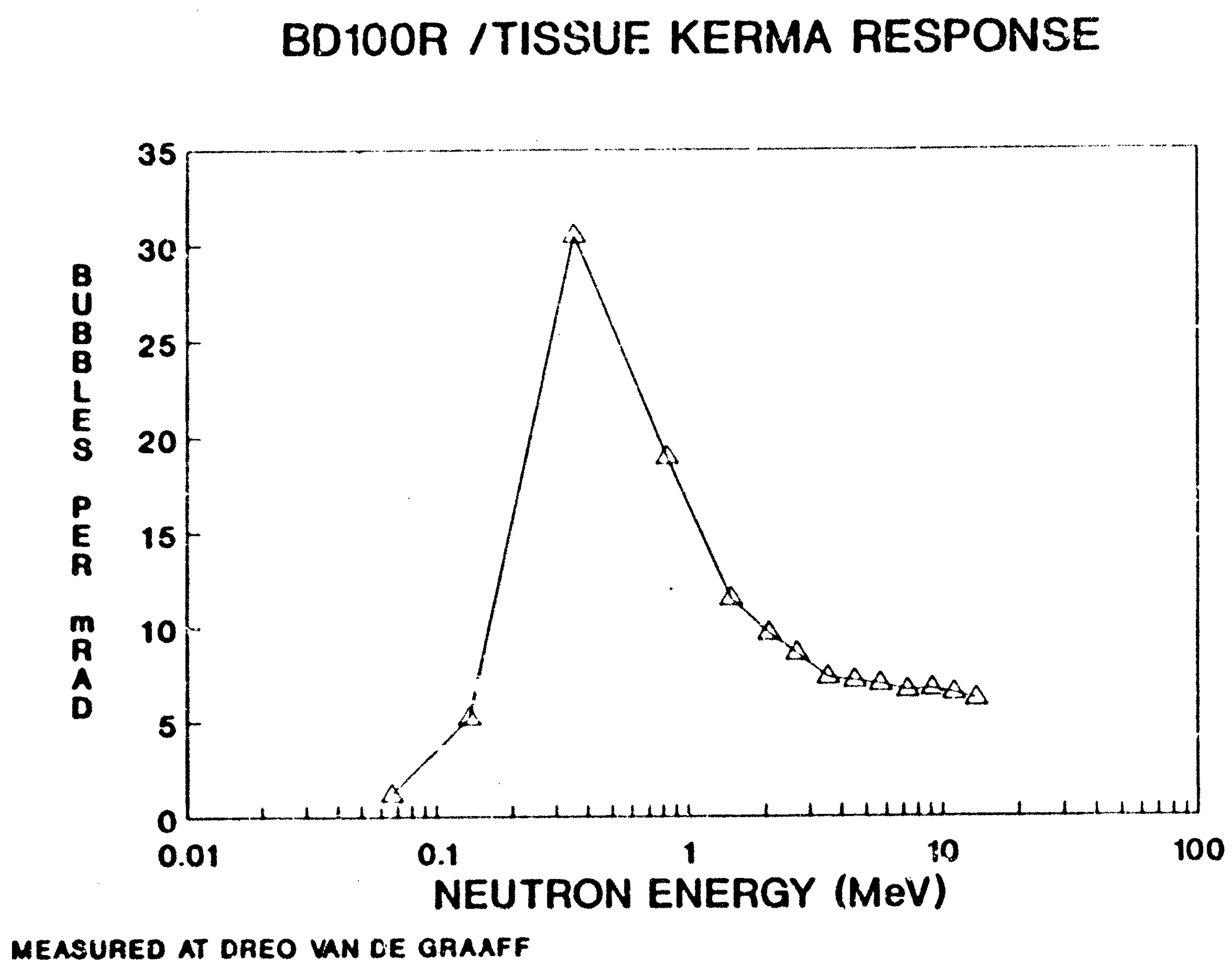

FIGURE 6 Ratio of bubble response per neutron tissue kerma showing a large peaking in the area of 300-400 keV.

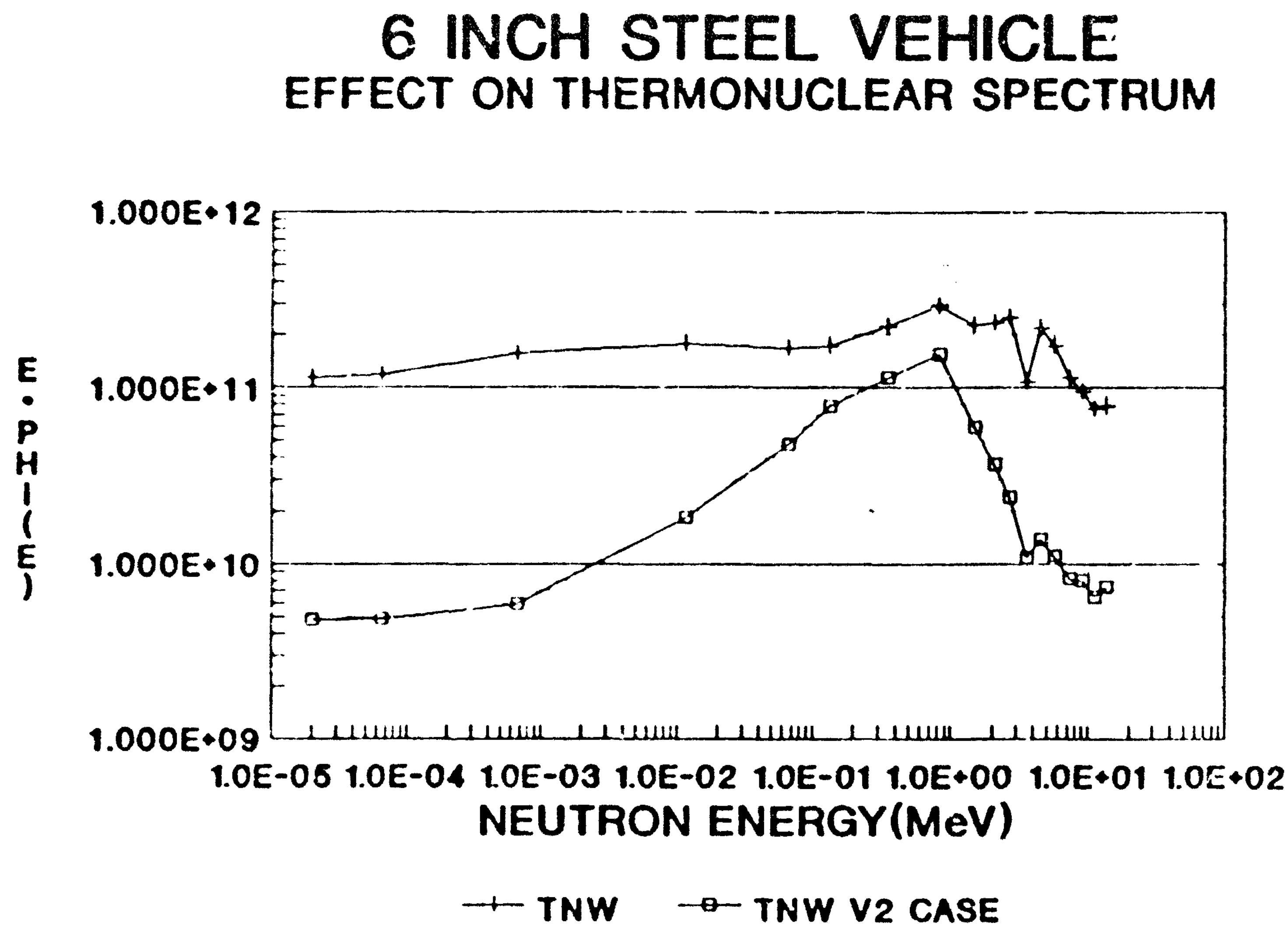

FIGURE 7 Free-field (ITI) and V2 neutron energy spectra for the TNW scenario as calculated by VPF2. Note' the maximum in the V2 spectra is a roughly the same energy as thge peak in the bubble per tissue kerma curve (Figure 6). This is responsible for the high values for bubble detector measured kerma predicted in the text.

Appendix A

SOURCE SPECTRA USED IN THIS REPORT

CASE	Group	Energy Boundaries (MeV)	SFW (Fraction in Group)	TNW (Fraction in Group)
	1	1.07×10^{-5} - 2.90×10^{-5}	0	0
	2	2.9×10^{-5} - 1.01×10^{-4}	0	0.0020
	3	1.01×10^{-4} - 1.23×10^{-3}	0	0.05719
	4	1.23×10^{-3} - 2.19×10^{-2}	0.01649	0.34417
	5	2.19×10^{-2} - 1.11×10^{-1}	0.20617	0.10964
N	6	.111 - .158	0.01799	0.01142
E	7	.158 - .550	0.15129	0.09058
U	8	.55 - 1.11	0.21587	0.0850
T	9	1.11 - 1.83	0.14678	0.0620
R	10	1.83 - 2.31	0.10173	0.02592
O	11	2.31 - 3.01	0.03871	0.02608
N	12	3.01 - 4.07	0.0548	0.02600
S	13	4.07 - 4.97	0.01177	0.01700
	14	4.97 - 6.36	0.01832	0.01800
	15	6.36 - 8.19	0.01274	0.01470
	16	8.19 - 10.0	0.00734	0.01410
	17	10.0 - 12.2	0	0.02560
	18	12.2 - 15.0	0	0.07060
	1	0.01 - 0.045	0.03259	
	2	0.045 - 0.10	0.01644	
	3	0.10 - 0.15	0.04881	
	4	0.15 - 0.30	0.10321	
	5	0.30 - 0.45	0.13571	
G	6	0.45 - 0.70	0.20256	
A	7	0.70 - 1.00	0.16332	
M	8	1.00 - 1.5	0.14073	
M	9	1.5 - 2.0	0.06429	
A	10	2.0 - 2.5	0.03743	
-	11	2.5 - 3.0	0.02225	
R	12	3.0 - 4.0	0.02109	
A	13	4.0 - 5.0	0.00746	
Y	14	5.0 - 6.0	0.00265	
S	15	6.0 - 7.0	0.00092	
	16	7.0 - 8.0	0.00038	
	17	8.0 - 10.0	0.00016	
	18	10.0 - 12.0	0	

Appendix B

SAMPLE OF CALCULATIONAL RESULTS
(ABBREVIATIONS EXPLAINED IN TEXT)

Group	Mean Neutron Energy (MeV)	SFW/5kT/LD50/FF Fluence in Group (n/cm^2)	SFW/5kT/LD50/V1 Fluence in Group (n/cm^2)
1	1.99×10^{-5}	3.64×10^{10}	3.14×10^{10}
2	6.50×10^{-5}	4.52×10^{10}	3.91×10^{10}
3	6.65×10^{-4}	8.94×10^{10}	7.36×10^{10}
4	1.16×10^{-2}	1.04×10^{11}	8.74×10^{10}
5	6.64×10^{-2}	7.07×10^{10}	4.65×10^{10}
6	1.35×10^{-1}	1.89×10^{10}	1.45×10^{10}
7	3.54×10^{-1}	7.42×10^{10}	4.85×10^{10}
8	8.30×10^{-1}	5.24×10^{10}	4.08×10^{10}
9	1.47	2.17×10^{10}	1.71×10^{10}
10	2.07	9.30×10^{9}	7.59×10^{9}
11	2.66	9.55×10^{9}	6.48×10^{9}
12	3.54	3.01×10^{9}	2.42×10^{9}
13	4.52	4.19×10^{9}	2.90×10^{9}
14	5.67	3.76×10^{9}	2.38×10^{9}
15	7.28	1.70×10^{9}	9.97×10^{8}
16	9.10	5.47×10^{8}	3.01×10^{8}
17	11.1	0	0
18	13.6	0	0

Appendix B (Continued)

SAMPLE OF CALCULATIONAL RESULTS
(ABBREVIATIONS EXPLAINED IN TEXT)

Group	Mean Neutron Energy (MeV)	TNW/5kT/ITI/FF Fluence in Group (n/cm^2)	TNW/5kT/ITI/V2 Fluence in Group (n/cm^2)
1	1.99×10^{-5}	1.05×10^{11}	4.41×10^{9}
2	6.50×10^{-5}	1.31×10^{11}	5.38×10^{9}
3	6.65×10^{-4}	2.64×10^{11}	1.00×10^{10}
4	1.16×10^{-2}	3.17×10^{11}	3.26×10^{10}
5	6.64×10^{-2}	2.24×10^{11}	6.38×10^{10}
6	1.35×10^{-1}	6.03×10^{10}	2.72×10^{10}
7	3.54×10^{-1}	2.47×10^{11}	1.26×10^{11}
8	8.30×10^{-1}	1.96×10^{11}	1.04×10^{11}
9	1.47	1.11×10^{11}	2.91×10^{10}
10	2.07	5.38×10^{10}	8.42×10^{9}
11	2.66	6.61×10^{10}	6.22×10^{9}
12	3.54	3.20×10^{10}	3.24×10^{9}
13	4.52	4.37×10^{10}	2.70×10^{9}
14	5.67	4.25×10^{10}	2.70×10^{9}
15	7.28	2.84×10^{10}	2.05×10^{9}
16	9.10	1.88×10^{10}	1.58×10^{9}
17	11.1	1.51×10^{10}	1.29×10^{9}
18	13.6	1.61×10^{10}	1.50×10^{9}

Appendix B (Continued)

SAMPLE OF CALCULATIONAL RESULTS
(ABBREVIATIONS EXPLAINED IN TEXT)

Group	Mean Neutron Energy (MeV)	14 MeV/100kT/ITI/FF Fluence in Group	14 MeV/100kT/ITI/V4 Fluence in Group
1	1.99×10^{-5}	6.77×10^{10}	3.79×10^{9}
2	6.50×10^{-5}	8.57×10^{10}	4.66×10^{9}
3	6.65×10^{-4}	1.74×10^{11}	9.22×10^{9}
4	1.16×10^{-2}	2.14×10^{11}	1.07×10^{10}
5	6.64×10^{-2}	1.50×10^{11}	7.62×10^{9}
6	1.35×10^{-1}	4.55×10^{10}	2.28×10^{9}
7	3.54×10^{-1}	1.89×10^{11}	1.07×10^{10}
8	8.30×10^{-1}	1.54×10^{11}	9.56×10^{9}
9	1.47	9.07×10^{10}	5.24×10^{9}
10	2.07	4.93×10^{10}	2.04×10^{9}
11	2.66	6.61×10^{10}	1.83×10^{9}
12	3.54	3.47×10^{10}	1.53×10^{9}
13	4.52	5.40×10^{10}	1.53×10^{9}
14	5.67	4.88×10^{10}	1.55×10^{9}
15	7.28	3.33×10^{10}	1.30×10^{9}
16	9.10	2.23×10^{10}	1.03×10^{9}
17	11.1	1.85×10^{10}	8.77×10^{8}
18	13.6	1.87×10^{10}	9.65×10^{8}

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The degree of protection from neutron irradiation afforded to electronics by armoured vehicles is most currently defined by the outside-to-inside ratio of the 1 MeV equivalent neutron fluence for Silicon. It has been proposed that this factor may be approximated by an experimentally measurable parameter - the neutron (tissue kerma) reduction factor. This report examines the validity of this assumption for a variety of realistic nuclear battlefield scenarios, calculated using the computer code VPF2. In addition the response of two neutron dosimeters in the calculated fields is examined.

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